The stone materials and their deterioration in the Angkor monuments, Cambodia

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1. Introduction

The Angkor monuments of Cambodia, which were constructed in the 9th century to the 13th century, were registered as the World Cultural Heritages by UNESCO in 1992. These monuments are distributed around Siem Reap, which is a town situated in the 250 km northeast of Phnom Penh, Cambodia(Fig. 1). Until now, about 700 monuments including 40 main monuments have been enumerated. Angkor Wat and Angkor Thom are the most famous among the Angkor monuments(Fig. 2).

The Angkor monuments were abandoned in the 15th century and since then have been covered and collapsed within the thick subtropical forest. The restoration of the monuments was initiated by the EFEO(L'Ecole Francaise D'Extreme-Orient, France) in 1907. After then, the restoration has been carried out by India, USA, Indonesia, Italy, Hungary, Germany and so on. Japanese government organized the Japanese Government Team for Safeguarding Angkor(JSA) in 1994 in order to restore and preserve the Angkor monuments. JSA consists of the specialists in the field of Architecture, Archaeology, Geology, Geotechnology, Petrology, Conservation Science, Surveying and so on. I visited the monuments nine times and investigated 30 monuments until now.

The purposes of the investigation by the Petrology Unit of JSA are as follows:
(1) description of the stone materials used for the monuments,
(2) specification of the quarries for the stone materials,
and (3) description and evaluation of the deteriorated stone materials.

The Angkor monuments are mainly made of sandstone and laterite. Brick is also used for sanctuaries of the relatively old monuments constructed in the 9th to the 10th century.

Fig. 1. Location of the Angkor monuments.

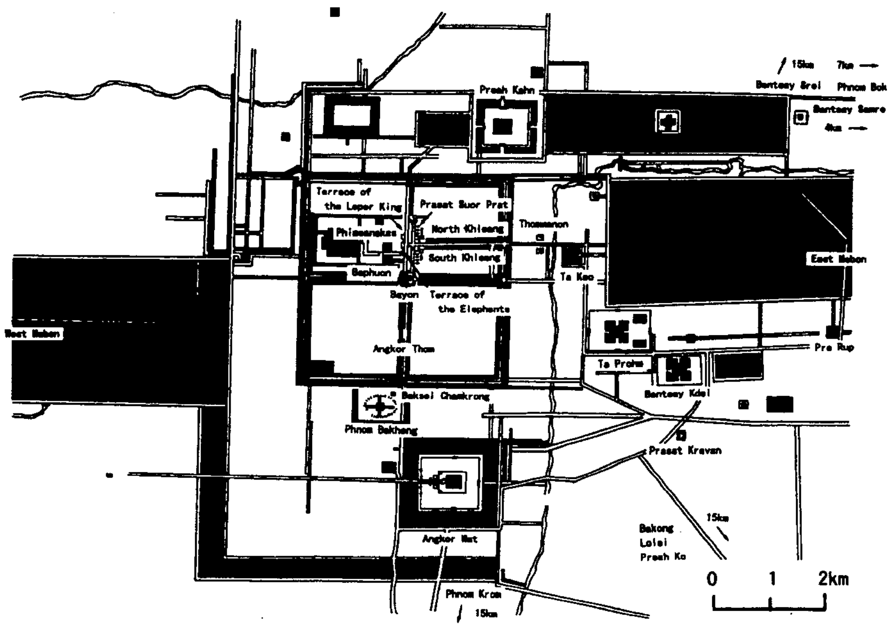

Fig. 2. Distribution of the monuments in the Angkor region.

2. Sandstones

2.1 Petrographic description of the sandstones

In the Angkor monuments, sandstones are used for important parts such as sanctuaries, surface of platforms and gate towers.

The sandstones used in the Angkor monuments can be classified into three types on the basis of the color, constituent mineral and texture: (1) grey to yellowish brown sandstone, (2) red sandstone, and (3) greenish greywacke. The grey to yellowish brown sandstone is the most popular sandstone in the Angkor monuments. The red sandstone is used only in Banteay Srei, but partly in North and South Khleangs. The greenish greywacke is limited in the sanctuaries of Ta Keo.

The grey to yellowish brown sandstone is used in all monuments except for Banteay Srei. This sandstone shows the color variation from grey to yellowish brown. The color variation is distinct especially for the monuments constructed after the late 12th century. The grey to yellowish brown sandstone consists mainly of fine- to medium-grained(0.1 to 0.3mm) quartz, feldspar (plagioclase and alkali feldspar), biotite, rock fragments and muscovite, and are accompanied by small amounts of magnetite, calcite, kaolinite, garnet, epidote, zircon and tourmaline. The detrital grains are angular to sub-angular but well sorted. This sandstone can be classified petrographically as feldspathic arenite. No difference in the texture and constituent mineral is found among the monuments investigated until now. Biotite and muscovite show the preferred orientation. This is one of the causes of deterioration of sandstone. Biotite tends to be altered into chlorite and goethite. The yellowish brown color of the sandstone is due to goethite.

The red sandstone consists mainly of fine-grained quartz(0.1 to 0.2mm in diameter), associated with a small amount of rock fragments(mainly chert), and is classified petrographically as quartz arenite. The detrital grains are rounded and well sorted. Fine-grained hematite and pyrite disseminate the interstices of the detrital grains. The color of the red sandstone is ascribed to hematite. Kaolinite is also detected by the X-ray diffractometer.

The greenish greywacke is used only for the sanctuaries of Ta Keo and characteristically hard compared with the other sandstones. The greenish greywacke consists mainly of feldspar(plagiocalse and alkali feldspar), quartz, rock fragments, biotite and muscovite. The detrital grains are angular and poorly sorted(<0.5mm). The greenish greywacke can be classified petrographically as feldspathic wacke.

2.2 Magnetic susceptibility of the grey to yellowish brown sandstones

2.2.1 Grouping of the monuments based on the magnetic susceptibility

The magnetic susceptibility of the sandstones is mainly attributable to magnetite contained in a small amount. The measurement was carried out for 50 sandstone blocks in each monument.

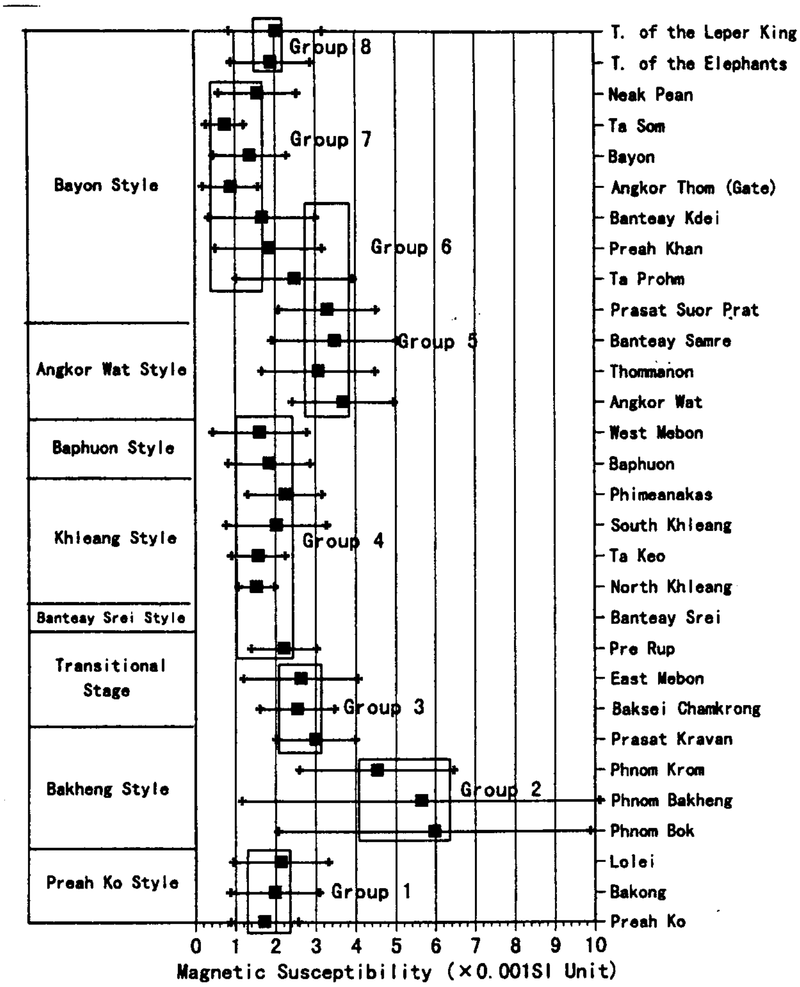

Fig. 3. Average magnetic susceptibility of the grey to yellowish brown sandstones used for the Angkor monuments (older to younger monuments from the bottom to the top).

The result is shown in Fig. 3. As mentioned above, the grey to yellowish brown sandstones of the Angkor monuments have the same texture and mineral composition, whereas they show a wide range of magnetic susceptibility from 0.7 to 6.0×10^{-3} SI unit in average. Based on the magnetic susceptibility of the grey to yellowish brown sandstones, the investigated monuments can be classified into 8 groups(Groups 1 to 8). The above fact indicates that the sandstones used for the same group have been supplied from the same quarry, and that the quarry of the sandstones have changed with the times.

2.2.2 Estimation of the construction sequence based on the magnetic susceptibility

It was clarified by Dumarcay and Grosier(1973) that Bayon was constructed in the four stages.

Thus we measured the magnetic susceptibility of the sandstones belonging to the each construction stage. As a result, the magnetic susceptibility of the sandstones increases 0.84(±0.48), 1.21(±0.48), 1.57(±1.03) to 2.23(±1.43)$\times10^{-3}$ SI unit(1σ standard deviation in parentheses) corresponding to the 1st, 2nd, 3rd and 4th construction stages, respectively.

In Ta Prohm, Preah Khan and Banteay Kdei belonging to the Group 6, the magnetic susceptibility of the grey to yellowish brown sandstones changes from place to place. Ta Prohm, Banteay Kdei and Preah Khan were constructed in the period between Angkor Wat belonging to the Group 5 and Bayon(Angkor Thom) belonging to the Group 7. The sandstones of Ta Prohm, Banteay Kdei and Preah Khan show the wide range of the magnetic susceptibility between those used for Angkor Wat and Bayon(Angkor Thom). This fact seems to suggest that the sandstones from the two different quarries must have been used for Ta Prohm, Preah Khan and Banteay Kdei.

2.3 Bulk chemical composition of the sandstones

Ten major components and 39 minor elements of the sandstones were analyzed by the instrumental neutron activation method and the inductively coupled plasma emission spectrometry(Activation Laboratories Ltd.).

No systematic difference in the chemical composition of the grey to yellowish brown sandstones corresponding to the grouping of the investigated monuments based on the magnetic susceptibility is found. The contents of major elements are almost 66 to 72% for SiO_2, 12 to 14% for Al_2O_3, 3.8 to 5.2wt% for total iron as Fe_2O_3, 1.6 to 2.6% for MgO, 0.9 to 3.3wt% for CaO, 2.5 to 3.1wt% for Na_2O and 1.8 to 2.3% for K_2O.

The chemical composition of the greenish greywacke is similar to that of the grey to yellowish brown sandstone in spite of difference in the texture. On the other hand, the red sandstone is relatively rich in SiO_2(87wt%).

2.4 Chemical compositions of plagioclase and garnet in the grey to yellowish brown sandstone

The chemical compositions of plagioclase and garnet contained in the grey to yellowish brown sandstones were analyzed by the energy dispersive X-ray microanalyzer.

Plagioclase: The content of orthoclase component in plagioclase is negligible, and almost plagioclase have the composition ranging from $Ab_{80}An_{20}$ to $Ab_{100}An_0$. No significant difference in the chemical composition of plagioclase was observed among the monuments.

Garnet: Small detrital garnet grains are commonly found in the grey to yellowish brown sandstone. As the contents of grossular and andradite end-members are less than 10 mol% in total. Almost garnet can be classified as almandine, and contain pyrope end-member up to 50 mol%(except for North Khleang, up to 70 mol%) and spessartine end-member up to 40 mol%. No systematic difference in the chemical composition of garnet was found among the monuments.

2.5 Orientation of the bedding plane of the grey to yellowish brown sandstones

The orientation of the bedding plane appeared on the sandstone blocks was investigated in each monument. The investigation was carried out for 100 to 150 sandstone blocks in each monument except for Angkor Wat and Bayon where 500 to 1000 sandstone blocks were examined. The enumeration was avoided for the sandstone blocks used for pillar and door and window frames.

The percentage of the sandstone blocks with the vertical bedding plane is high, 30 to 50%, for the relatively old monuments from Preah Ko to West Mebon. On the other hand, the percentage is low, about 10%, for the younger monuments from Angkor Wat to Terrace of the Leper King(Fig. 3). In the younger monuments, the sandstone blocks with the vertical bedding plane are used only as wedge stones. The above fact may suggest that in the early time of the construction of the Angkor monuments, they did not take into account the orientation of the bedding plane, but that 200 years later from the beginning of the construction, they began to construct the monuments by setting the bedding plane of the sandstone parallel or nearly parallel to the horizontal plane.

3. Laterites

3.1 Petrographic description of the laterites

Laterites are generally used for platforms(surface and interior), surrounding walls and pavements.

The laterites used in the Angkor monuments are reddish to yellowish brown in color, and can be classified into two types on the basis of petrographic texture, namely porous laterites and pisolitic laterites. The porous laterites have large pores up to a few centimeters in diameter on the surface. It seems that the pores were originally filled with kaolinite and then it was washed away by rain water. The pisolitic laterites consist mainly of pisolite of 5 to 10mm in diameter. There exist laterites with the intermediate texture between porous laterites and pisolitic laterites.

3.2 Constituent minerals

The laterites consist of reddish brown materials constituting pisolite and network frame of porous laterite, and white to yellowish white materials filling the pores. X-ray diffraction analysis revealed that the reddish brown materials consist mainly of hematite and goethite. On the other hand, the white to yellowish white materials consist mainly of kaolinite. Quartz is common in the both materials.

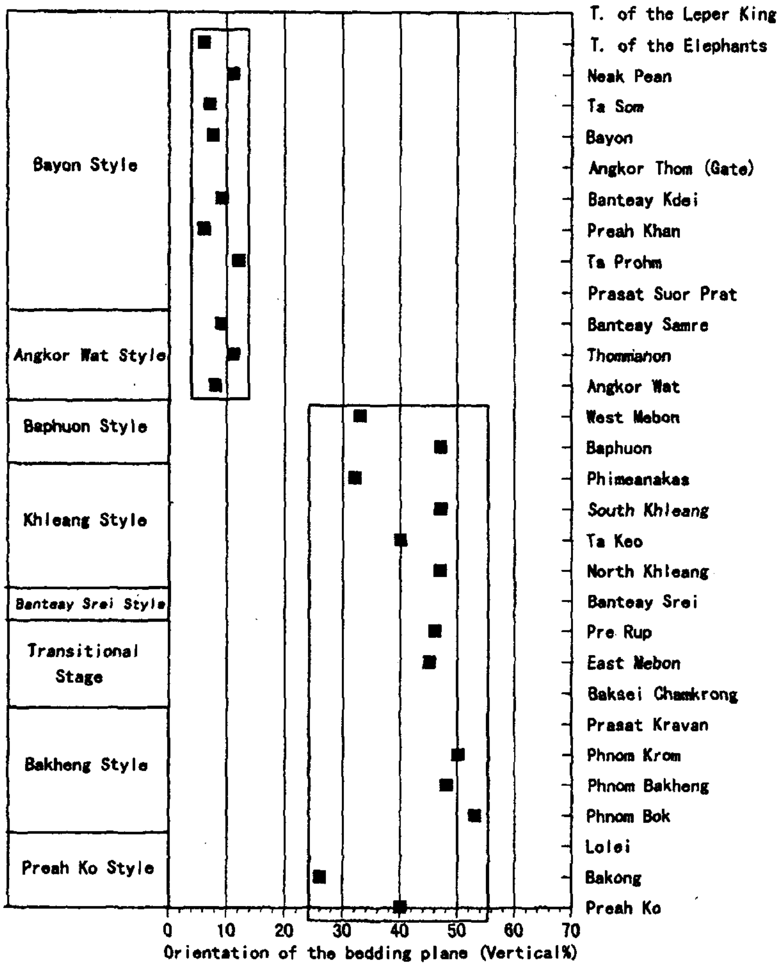

Fig. 4. The percentage of the grey to yellowish brown sandstone blocks with the vertical bedding plane (older to younger monuments from the bottom to the top).

3.3 Original rock

The laterites used in the Angkor monuments contain pebbles and are heterogeneous under the microscope. The texture of the original rock is frequently preserved in laterites suffered weak lateritization. Judging from the texture, the laterites are supposed to be derived from sandstones and conglomerates.

3.4 Pore size

The size of the representative pores for 50 laterite blocks was measured and then the average

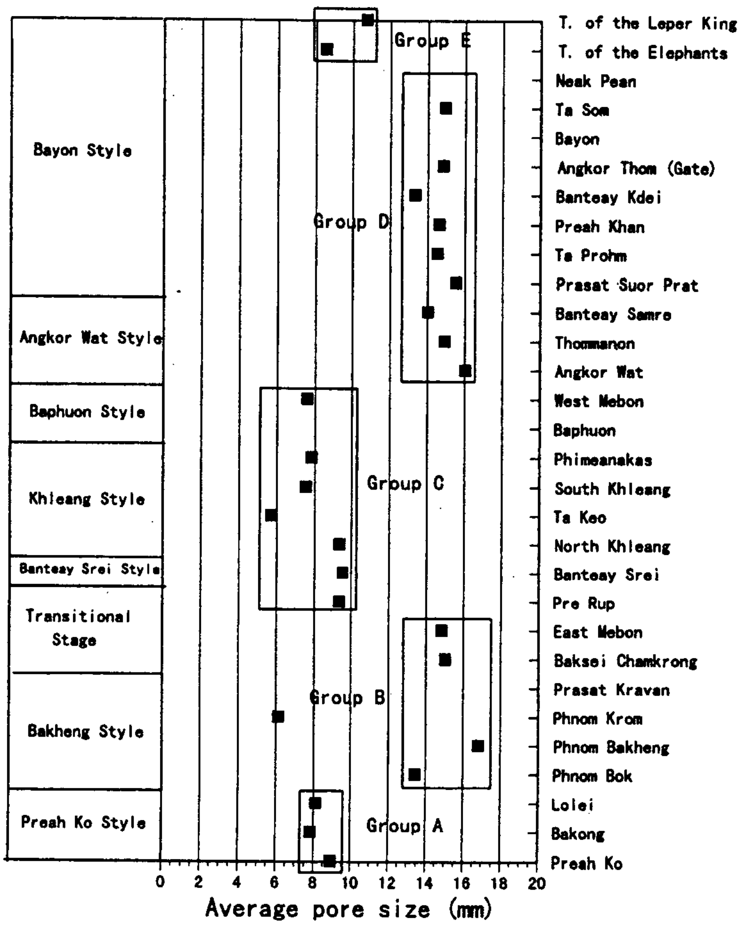

Fig. 5. Average pore size of the laterites used for the Angkor monuments(older to younger monuments from the bottom to the top).

pore size was calculated. The result is summarized in Fig. 5. Taking into account the construction age, the investigated monuments except for Phnom Krom can be classified into the 5 groups.

3.5 Magnetic susceptibility

Figure 6 summarize the average magnetic susceptibility of the laterites used in the investigated monuments. The measurement was carried out for 50 laterite blocks in each monument.

The average magnetic susceptibility of the laterites in the Angkor monuments ranges from 0.3 to 1.7×10^{-3} SI Unit. Based on the magnetic susceptibility of the laterites, the investigated monuments seem to be classified into the five groups. The grouping based on the magnetic susceptibility is concordant with that based on the pore size. However Phnom Krom and Banteay Srei are exceptions.

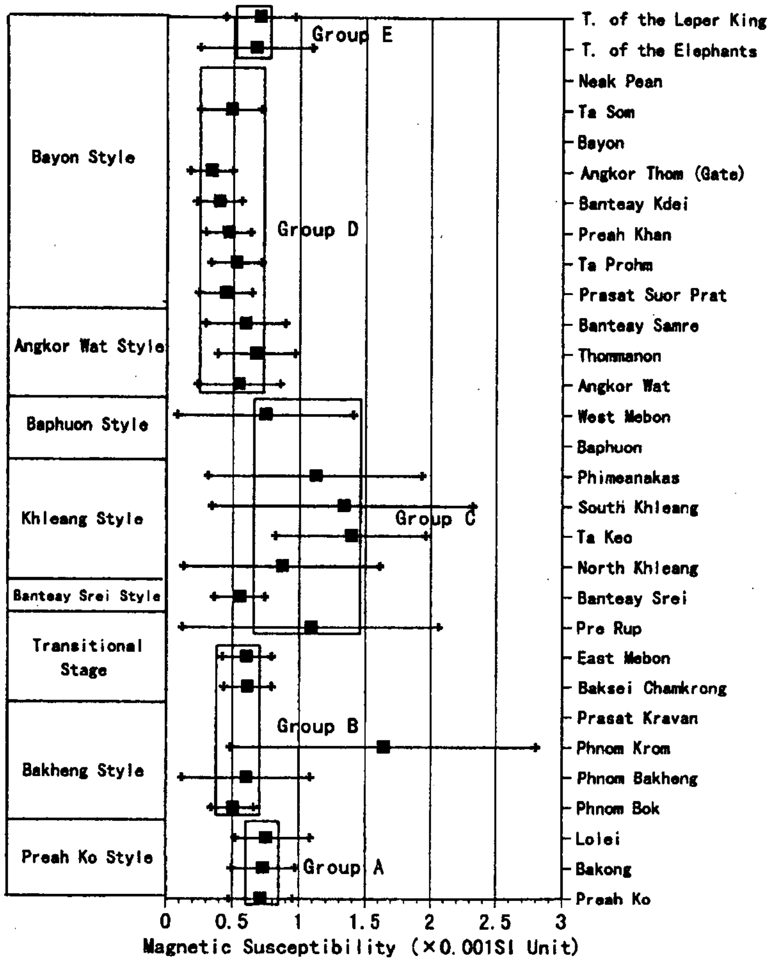

Fig. 6. Average magnetic susceptibility of the laterites used for the Angkor monuments (older to younger monuments from the bottom to the top).

3.6 Bulk chemical composition

The bulk chemical composition(49 elements) of the laterites was determined(Activation Laboratories, Ltd.). Major components of the laterites are SiO_2(20 to 50wt%), Al_2O_3(12 to 22wt%) and Fe_2O_3(total iron)(23 to 50wt%), and the laterites have large ignition loss(9 to 13wt%). The laterites of the Groups A, C and E in Figs. 5 and 6 are rich in Fe_2O_3, but poor in SiO_2 compared with those of the Groups B and D of the same figures.

In regard to minor elements, there found systematic difference in As, Sb, Sr and V contents. The laterites of the Groups A, C and E are rich in As, Sb and Sr, but poor in V compared with those of the Groups B and D.

3.7 Orientation of the bedding plane

The orientation of the bedding plane was investigated for more than one hundred of laterite blocks in each monument. As a result, it was revealed that the percentage of the laterite blocks with the vertical bedding plane is high(30 to 75%) in the monuments constructed prior to Angkor Wat, but low(less than 14%) in Angkor Wat and subsequently constructed monuments. This result is in accord with that obtained for the sandstones. However, the percentage is exceptionally low(3%) in Preah Ko, which is the oldest monument.

4. Deterioration of sandstones

4.1 Physical properties of sandstones

4.1.1 Porosity

The porosity of the sandstones was measured by the water saturation method and was obtained to be 13 to 19% for the grey to yellowish brown sandstone, 11 to 15% for the red sandstone and about 2% for the greenish greywacke.

4.1.2 Uniaxial compressive strength

The rebound value was measured by a Schmidt rock hammer. The measurement was made on the smooth surface of 50 sandstone blocks in each monument, and the average rebound value was obtained. The average values are 45 to 54 for the grey to yellowish brown sandstone, 53 for the red sandstone and 64 for the greenish greywacke. Based on the relationship between the uniaxial compressive strength and the rebound value obtained by Haase(1965), the uniaxial compressive strength of the grey to yellowish brown sandstone, the red sandstone and the greenish greywacke are estimated to be 320 to 440 kg/cm^2, 430 kg/cm^2 and 800 kg/cm^2, respectively.

The P-wave propagation velocity was measured for fallen sandstone samples collected from the monuments, using a PUNDIT(C.N.S. Electronics).

The measured P-wave propagation velocities along the bedding plane are 1.9 to 3.2 km/sec for the grey to yellowish brown sandstone, 3.9 to 4.0 km for the red sandstone and 4.4 km/sec for the greenish greywacke. Based on the relationship between the P-wave propagation velocity and the uniaxial compressive strength by Okubo and Terasaki(1971), the uniaxial compressive strength of the grey to yellowish brown sandstone, the red sandstone and the greenish greywacke are estimated to be 70 to 300 kg/cm^2, 700 kg/cm^2 and 900 kg/cm^2, respectively. The uniaxial compressive strength of the grey to yellowish brown sandstone estimated from the P-wave propagation velocity is considerably lower than that estimated from the rebound value. This may suggest that the stone samples used for the measurement of the P-wave propagation velocity

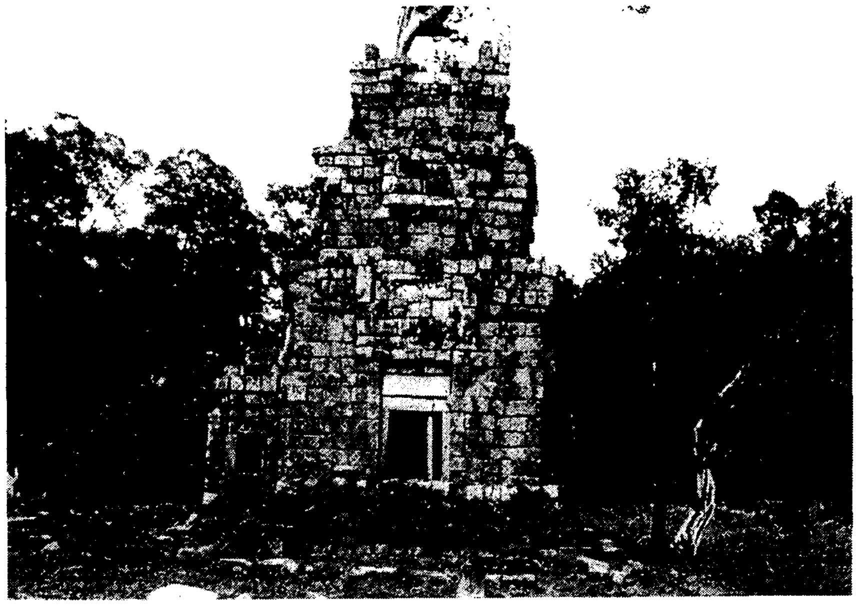

Fig. 7. S1 tower of Prasat Suor Prat inclinging to the pond due to differential settlement of the ground.

are more or less deteriorated because they are all fallen blocks.

4.2 Factors controlling the collapse of the monuments

The followings are considered as factors controlling the collapse of the Angkor monuments.

4.2.1 Differential settlement

Differential settlement of the ground is remarkable in N1 to N3 and S1 towers of Prasat Suor Prat(Fig. 7), and in Bayon. There are artificial ponds nearby N1 to N3 and S1 towers of Prasat Suor Prat, and around Bayon. Therefore, it is supposed that this situation caused the differential settlement of the ground. These towers are inclined toward the ponds. The stress concentration thus occurred brought the destruction of laterites in the lower part of the towers and sandstones of the window frame. Also in Bayon, the differential settlement may have brought the collapse of the roof of the outer gallery because no deterioration of the pillars is observed.

4.2.2 Strength of the stone materials

The uniaxial compressive strength of the sandstones was estimated as greenish greywacke > red sandstone > grey to yellowish brown sandstone by non-destructive methods mentioned above. No remarkable deterioration is observed in the greenish greywacke and red sandstone. On the other hand, exfoliation and cracking along bedding planes are frequently observed in the grey to yellowish brown sandstone blocks emplaced with their bedding planes vertically. Window and door frames, pillars and balusters are the typical examples. As described above, a large amount of biotite is contained in the grey to yellowish brown sandstone, and biotite shows the preferred orientation along bedding planes. Because cleavage is well developed in biotite, the grey to yellowish brown sandstone tends to de-laminate along bedding planes. Therefore, if sandstones will be piled up as their bedding plane is vertical, the sandstones tend to break along the bedding plane and deterioration progresses along the cracks. Phnom Krom is a typical example.

4.2.3 Weathering of the sandstones

(1) Chemical weathering

The chemical weathering of stone materials seems to be intimately related to the constituent minerals, porosity and water supply. Among the constituent minerals of the sandstones used in the Angkor monuments, feldspar and biotite tend to be affected by alteration, whereas quartz is resistant to the chemical weathering. Thus the red sandstone consisting mainly of quartz shows no deterioration in spite of its high porosity. Though abundant feldspar and biotite occur in the greenish greywacke as well as in the grey to yellowish brown sandstone, the greenish greywacke shows no remarkable deterioration except for partial exfoliation. This is because of a low porosity of the greenish greywacke(2%). On the other hand, the grey to yellowish brown sandstone has a high porosity(13 to 19%) and thus seems to be prone to chemical weathering if the water supply is sufficient. In fact, the deterioration of the grey to yellowish brown sandstone is frequently observed in the lower part of walls and pillars due to the ascension of water by capillary action. The pillars of the outer gallery in Bayon show no deterioration in appearance. However, P-wave propagation velocity decreases in the lower part, especially within 60 cm above the floor. This suggests that the deterioration progresses in the lower part due to the water supply by capillary suction. The deterioration of pillars can also be monitored well by the magnetic susceptibility because magnetite which is the determinative mineral for the magnetic susceptibility of the sandstones will be changed into goethite due to alteration. The magnetic susceptibility of the pillars decreases downward, especially within 60 cm above the floor.

(2) Efflorescence related to bat guano

The deterioration of the sandstones is severe in Phnom Krom, Angkor Wat and Bayon among the Angkor monuments. Because gypsum and phosphate minerals were found from deteriorated rocks, it seems that the deterioration is attributable to efflorescence related to guano of bat which still continues to live in the monuments.

Phnom Krom is the most severely deteriorated monument among the Angkor monuments. The color of the sandstone used for the sanctuaries changed to yellowish brown due to the formation of goethite. The sandstone shows exfoliation, and most reliefs on the surface are detached. As mentioned above, the percentage of the sandstone blocks with vertical bedding planes is highest(more than 50%) in Phnom Krom among the Angkor monuments. This also seems to be related to the severe deterioration of the sandstone.

In Angkor Wat, the towers of the middle gallery and the lower parts of pillars and walls of all galleries are places where the deterioration of the sandstone associated with efflorescence from bat guano is most severe(Fig. 8). The considerable exfoliation of the sandstone is observed in the outer wall of the towers of the middle gallery and phosphate minerals are formed on the surface. The surface of the towers is tinted yellowish brown. The sandstone used in the lower part(within about 50 cm above the floor) of walls and pillars in the galleries become white and show exfoliation. The exfoliation is also observed in the lower part of the door and window frames in the galleries.

In Bayon, the exfoliation is severe in the inner wall of the central sanctuary. The deterioration of the sandstones is also found in the inner wall of the towers near the central sanctuary.

The deteriorated sandstones tend to be rich in MgO, CaO, P_2O_5 and SO_3 compared with fresh sandstones. Little SO_3 is contained in the fresh sandstones, whereas elevated levels of SO_3 were detected in the deteriorated sandstones. P_2O_5 is also concentrated in the deteriorated sandstones. Guano of bat living in the monuments is supposed to be a source supply of P_2O_5 and SO_3. The following phosphate minerals were identified from the deteriorated sandstone samples: brushite, newberyite, whitlockite and taranakite.

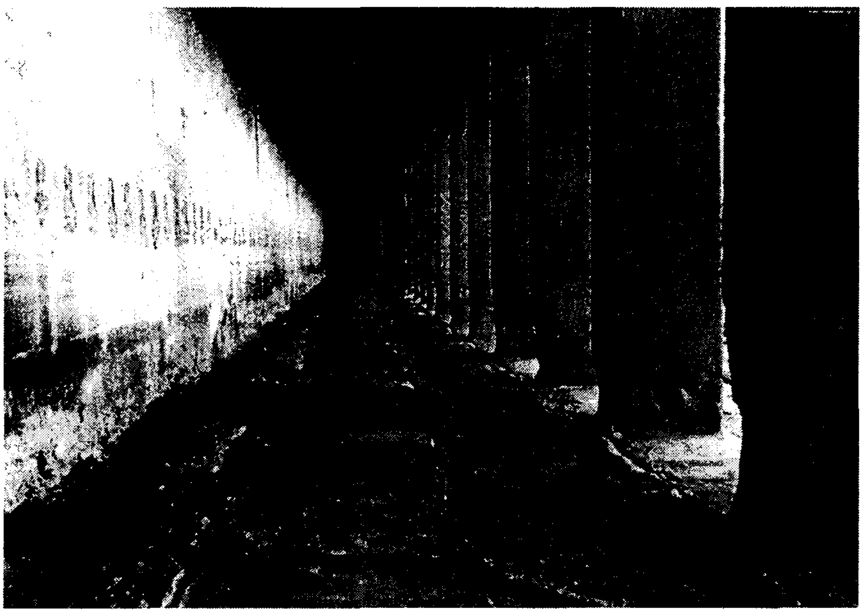

Fig. 8. Deterioration of the sandstones due to efflorescence related to bat guano, observed in the lower part of the pillars and wall in the Outer Gallery of Angkor Wat.

Fig. 9. Roots of a tree growing on the monument(Ta Prohm).

(3) Salt weathering related to calcite precipitation

The exfoliation of the sandstones due to calcite precipitation is frequently observed in the inside of the buildings. The mechanism is as follows: (1) rain water infiltrates from the surface of the buildings to the inside dissolving calcium, (2) calcium precipitates near the inner surface as calcite in the reaction with carbon dioxide in the air when water evaporates from the inner surface of the buildings, and finally (3) the exfoliation of the sandstone surface occurs due to crystallization pressure of calcite. This type of exfoliation is also observed in the outer surfaces of the buildings which are not exposed to the rain. The exfoliation observed on the surfaces of platforms seems to occur in the same process. Phnom Bakheng and Ta Keo are the typical examples.

4.2.4 Biological activity

As the Angkor monuments had been left in a jungle for a long time, growth of plants influenced severely the collapse of the monuments. The plants were almost cleaned out now, so we cannot see the Angkor monuments covered with plants. However, Ta Prohm is a typical case of the destruction by plants and is preserved as it was(Fig. 9). The S6 tower of Prasat Suor Prat was also destroyed by the plant. Lichen on the surface of sandstone causes the deterioration of the surface of the sandstones. Bayon and Phimeanakas are mostly covered with lichen.

4.2.5 Construction method

Corbel arch structure is used for the roofs of the Angkor monuments. Also no adhesive is used for the stone materials. Therefore, the monuments tend to be affected easily by the above factors. Conversely speaking, the corbel arch structure itself may be the most important factor for the collapse of the Angkor monuments.

4.2.6 Human activity

Because the guard of the monuments is not sufficient, theft of sculptures continues. Bullet holes due to a civil war since 1970's are often found on the rock surfaces.

4.2.7 Natural disaster

It is possible to consider that natural disaster such as wind collapsed the monuments. Geotechnical, geological and environmental survey Unit of JSA reported that the strong wind reaching 40 m/s was recorded. There is a possibility that such strong wind moves stone blocks gradually and finally brings the monuments to the collapse.

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